

Effects of proximity to offshore fish farms over soft-bottom macrofauna

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Sea-cage fish farms impact the seabed within their immediate vicinity, potentially affecting recipient communities. We assessed whether proximity to three sea-cage fish farms at the Canary Islands altered patterns in the abundance, assemblage structure and richness of soft-bottom macrofauna. We related among-farm variability in dissimilarities in macrofaunal assemblage structure between seabeds beneath cages and controls to differences in hydrodynamics, production and seabed topography. Contrasting patterns of species abundances with varying proximity to fish farms were observed: some species decreased while other species increased their abundances with increasing distance at some farms. Although faunal assemblages at 0 m (i.e. beneath the cages) were different, in terms of assemblage structure, from those found at controls, pairwise differences in assemblage structure among distances away varied among the studied fish farms. Species richness showed inconsistent patterns with proximity to cages among fish farms. In summary, inconsistent patterns of macrofaunal assemblages with varying proximity to aquaculture facilities preclude confident predictions on the way offshore aquaculture alters macrofauna in the study region.

Keywords: aquaculture, macrofauna, impact, sandy seabeds, Canary Islands, Atlantic Ocean

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INTRODUCTION

Since the initial development of sea-cage offshore (i.e. open ocean) aquaculture in the early 1980s, the number of sea-cage fish farms has increased rapidly throughout coastal areas of the world to produce almost 60 million tons of fish every year (FAO, 2010). Offshore aquaculture facilities are often installed in open areas with high water renovation, i.e. exposed to currents and located at greater depths relative to those located in fjords and shallow enclosed bays. Because of these oceanographic conditions, the level of environmental perturbation is expected, at least theoretically, to be low.

The environmental impacts of sea-cage fish farms have received attention in the last few decades (Gowen & Bradbury, 1987; Kalantzi & Karakassis, 2006; Giles, 2008). These include, among others, impacts on biogeochemical processes, alterations over the distribution of benthic communities, including sensitive habitats such as seagrasses and maërl beds, and transfer of antibiotics and other therapeutics to the environment (Iwama, 1991; Rönnenberg *et al.*, 1992; Ruiz *et al.*, 2001; Sanz-Lazaro & Marin, 2011). One of the effects on the seabed is the accumulation of organic matter, which affects the sediment structure in different ways (Holmer & Kristensen, 1992; Holmer *et al.*, 2005): (i) increasing the oxygen demand, (ii) creating hypoxic layers and (iii) even anoxic sediment. These processes boost anaerobic metabolism

(mainly sulphate reduction) (Middleburg & Levin, 2009) and enhance the emission of associated toxic gases (Pusceddu *et al.*, 2007; Hargrave *et al.*, 2008). These changes can modify the composition and abundance of benthic organisms (Tomasetti *et al.*, 2009; Edgar *et al.*, 2010). For example, a clear dominance of capitellids (e.g. *Capitella* cf. *capitata*), dorvilleids (*Ophiotrocha* spp.) and cirratulids (*Tharyx heterochaeta* and *Chaetozone* spp.) has been observed in sediments beneath fish cages (Lu & Wu, 1998; Karakassis *et al.*, 2000; Lee *et al.*, 2006; Hall-Spencer *et al.*, 2006; Aguado-Gimenez *et al.*, 2007; Kutti *et al.*, 2007; Edgar *et al.*, 2010). The area of influence of cages largely depends on local factors, such as hydrodynamic conditions, cage feeding management and production, seabed topography and depth (Giles, 2008; Borja *et al.*, 2009). In fact, the area affected by organic matter enrichment may vary from tens of metres up to several kilometres (Holmer *et al.*, 2008a, b). This pattern follows the 'Pearson–Rosenberg' theory; a prominent model of spatial organic enrichment gradient. Typically, these differences in the composition and abundance of faunal assemblages with varying proximity to sea-cage fish farms follow this 'zonation' pattern, consisting of three distinct areas (Dimech *et al.*, 2002): (i) the area occupied by fish cages, characterized by a low species richness and the dominance of grazers and depositivorous fauna; (ii) the area located on the surroundings of the fish cages (typically between 30 to 90 m away from the farm), characterized by the highest species richness and abundances; and (iii) the area not directly affected by fish cages (>100 m away), with intermediate values of species richness and abundances and a representation of a wide spectrum of trophic guilds (grazers, depositivorous, suspensivorous and

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predators). Yet, inconsistent results among studies have been detected and attributed to environmental drivers, such as sedimentary composition (i.e. grain size composition) and local hydrodynamics (reviewed by Sanz-Lazaro & Marin, 2011).

In this study, we assessed whether proximity to three sea-cage fish farms altered patterns in the abundance, assemblage structure and species richness of soft-bottom macrofauna in a predictable way.

MATERIALS AND METHODS

Study area and sampling strategy

This study was conducted around three sea-cage fish farms at the Canary Islands (NE Atlantic Ocean, 28°N), one located off Gran Canaria (Melenara) and two off Tenerife (Caletillas and Los Cristianos), which culture the same fish species, the gilt-head sea bream *Sparus aurata* and the sea-bass *Dicentrarchus labrax*, but under different production conditions (Figure 1, see Table 1 for details on production and culture conditions). Collection of samples took place, by scuba-divers, at 0, 20, 40 and 60 m away and at two controls, between 0.5–1 km away, from each fish farm. One control was upstream and the other downstream of the main current, based on previous hydrodynamic studies from the Canary Archipelago (Table 1) (Barton *et al.*, 2000, 2001). Controls had a similar depth and grain size composition relative to fish farms (25–30 m depth). Stations at 0 m (27–30 m depth) were established beneath the cage located in the farm perimeter that was exposed to the main current; from here, the sampling stations followed a transect running parallel to the downstream current. Sediment cores (20 cm inner diameter) were pushed into the sediment to a depth of 20 cm; this size is within the standard range used to study macrofaunal assemblages (e.g. Heilskov *et al.*, 2006; Gillet *et al.*, 2007). Three replicates per sampling station were randomly collected for faunistic determinations and one core

for sediment grain size composition. This replication level has been used in monitoring assessment studies (e.g. Del-Pilar-Ruso *et al.*, 2009; Riera *et al.*, 2012), including offshore fish cages (Grego *et al.*, 2009). The samples were collected during spring–summer 2011 (Table 1).

Environmental conditions at each fish farm

To assess the sediment grain size composition of each sample, ~100 g of sediment was oven dried at 105°C, passed through a graded series of sieves (2, 1, 0.5, 0.25, 0.125 and 0.063 mm), and then weighed (Buchanan, 1984). These sieves characterized seven different sedimentary types (gravels, very coarse sands, coarse sands, medium sands, fine sands, very fine sands and silt/clay). Current velocities at each fish farm were measured by Acoustic Doppler Current Profilers (ADCPS, models Argonaut-XRand and FlowQuest 600). ADCPSs recorded current velocity every 30 min in 10 layers covering the entire water column (see Table 1 for details).

Patterns of faunal assemblages with proximity to fish farms

Faunal samples were preserved in a 10% seawater formaldehyde solution, and subsequently decanted through a 0.5 mm mesh sieve. The fraction remaining was separated into different taxonomic groups under a binocular microscope, and preserved in 70% ethanol. Macrofaunal specimens were determined to species level, whenever possible, by means of a binocular microscope, or a Leica DMLB microscope equipped with Nomarski interference.

To visualize affinities in faunal assemblage structure according to varying proximity from each fish farm, a NMDS (non-metric multidimensional scaling) was carried out on square-root transformed abundance data via the Bray–Curtis similarity, separately for each farm. Differences in faunal assemblage structure with varying proximity to each fish farm (i.e. distance: 0, 20, 40, 60 m and controls) were tested by means of a Permutational Multivariate

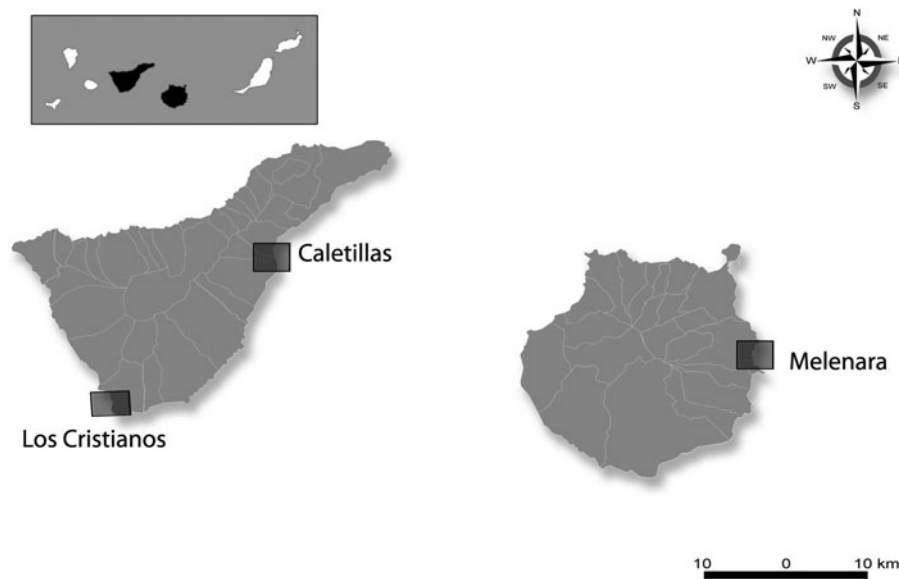


Fig. 1. Map of the study area, showing location of the three sea-cage fish farms.

Table 1. Location, production and environmental data of each sea-cage fish farm.

	Caletillas (Tenerife)	Los Cristianos (Tenerife)	Melenara (Gran Canaria)
Geographic location	28°22'53"N 16°21'09"W	28°02'04"N 16°42'46"W	27°58'17"N 15°22'15"W
Year of installation	2007	1999	1992 (relocated in 2000)
Number of cages per farm	6	12	22
Average production (t y ⁻¹)	200	500	750
Type of seabed	Unvegetated sandy	Unvegetated sandy	Unvegetated sandy
Dominant grain size	Medium and fine sands	Fine sands and very fine sands	Fine sands and very fine sands
Mean surface current speed	12.8 ± 4.3 cm s ⁻¹	6.5 ± 2.3 cm s ⁻¹	10.5 ± 4.5 cm s ⁻¹
Mean bottom current speed	20.8 ± 5.6 cm s ⁻¹	11.3 ± 3.8 cm s ⁻¹	16 ± 4.3 cm s ⁻¹
Period of sampling	April 2011	May 2011	June 2011
Location of current-meters	28°21'17"N, 16°16'14"W	28°06'14"N, 16°44'54"W	27°58'36"N, 15°22'23"W
Set up period of current-meters	5 April 2009–5 May 2009	7 February 2011–6 March 2011	3 February 2011–4 March 2011

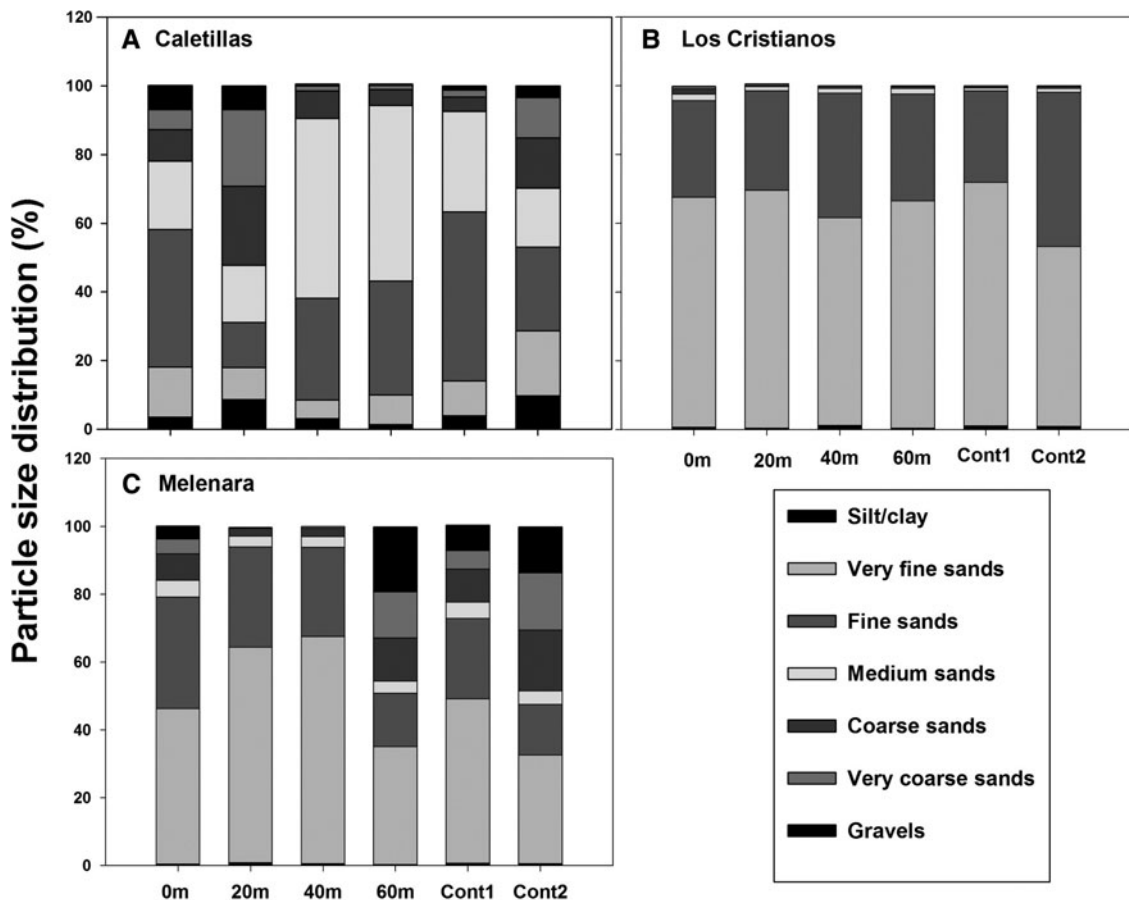
ANOVA (PERMANOVA) that included the factors: 'Distance' (fixed factor) and 'Farm' (random factor, orthogonal to 'Distance'). The same model, but in a univariate context via permutation-based ANOVAs, was used to test for differences in the abundance of the most conspicuous species, including *Ampelisca brevicornis*, *Apseudes talpa*, *Dasybranchus caducus*, *Ditrupa arietina*, *Platynereis dumerilii*, *Scoloplos armiger* and *Urothoe marina* – these species accounted for ~78% of total individuals observed – as well as for species richness. In all cases, P values were obtained through 4999 permutations of the raw data under a reduced model. Because variances remaining heterogeneous in most cases regardless of transformations, we reduced Type I error using an α value to 0.01 (Underwood, 1991). Pairwise tests

were used to resolve differences in faunal assemblage structure, species abundances and species richness among distances separately for each farm when significant 'Distance × Farm' interactions were detected (i.e. all distances were compared for each farm). All multivariate procedures were carried out via the PRIMER 6.0 and PERMANOVA+ statistical package.

RESULTS

Environmental conditions at each fish farm

Caletillas was dominated by medium and fine sands (Figure 2A), while Los Cristianos and Melenara were

**Fig. 2.** Sediment grain size composition with varying proximity from each fish farm.

dominated by fine and very fine sands (Figure 2B, C, respectively); these granulometric patterns were linked with larger current speeds at Caletillas relative to Los Cristianos and Melenara (Table 1).

Faunal assemblages with varying proximity to fish farms: species-level patterns

A total of 13,579 specimens were collected, belonging to 15 taxonomic groups, including: Amphipoda, Cumacea, Decapoda, Echinodermata, Isopoda, Leptostraca, Mollusca, Nematoda, Nemertea, Oligochaeta, Ostracoda, Polychaeta,

Sipuncula, Stomatopoda and Tanaidacea (Appendix 1>). In terms of species, 177 taxa were recorded; polychaetes (70 species) and molluscs (33 species) were the most conspicuous groups. In contrast, leptostraceans and stomatopods were exclusively represented by one species (Appendix 1). We observed contrasting patterns of abundance among species with varying proximity to fish farms (Figure 3). Some species significantly decreased their abundances with increasing distance from some fish farms, e.g. *Platynereis dumerilii* (Figure 3E) at Melenara and *Dasybranchus caducus* (Figure 3C) at Los Cristianos (Table 2, pairwise comparisons). In contrast, some species increased their abundances with increasing distance from fish farms, e.g. *Apeudes talpa*

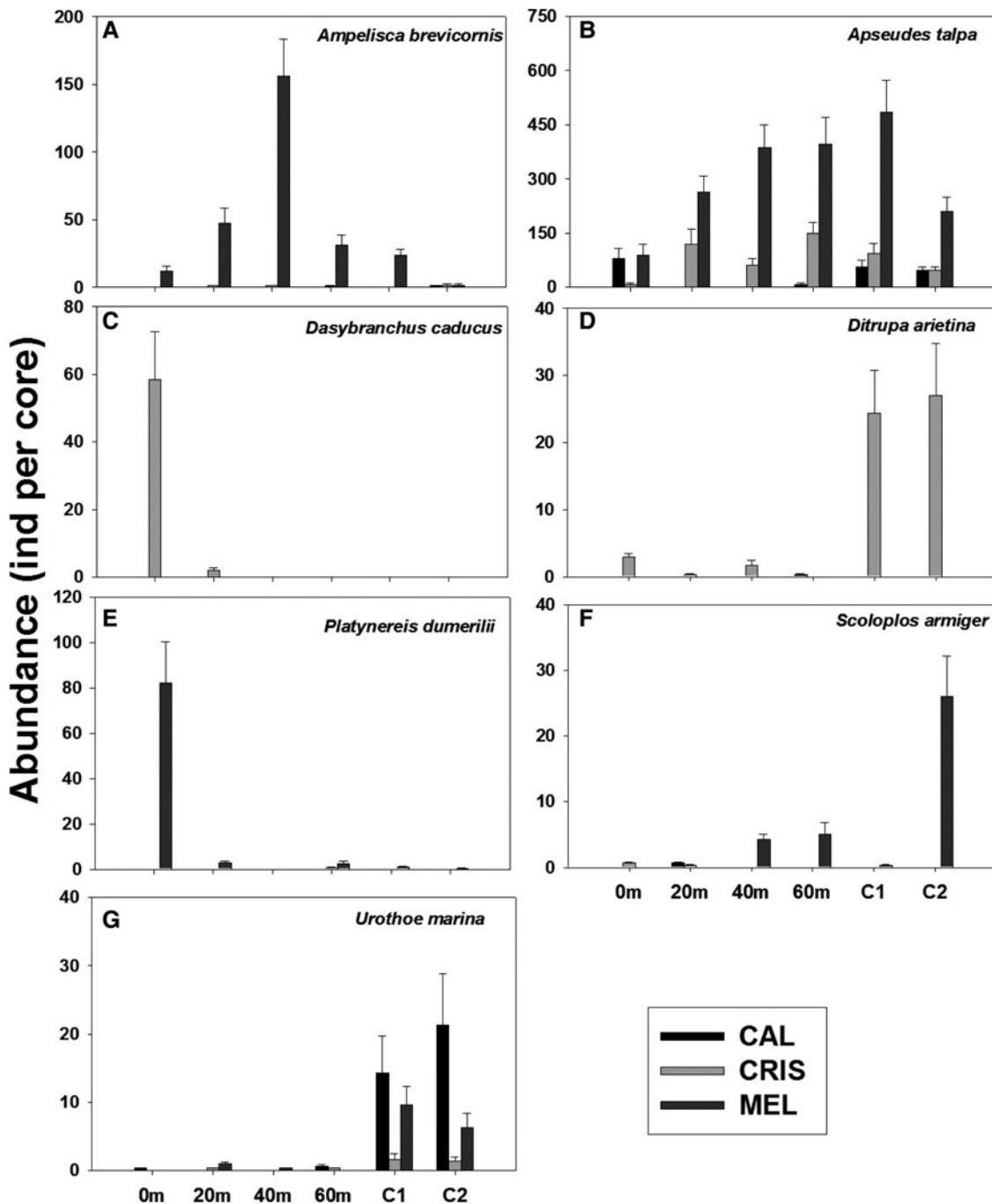


Fig. 3. Abundances of the most conspicuous macrofaunal species at varying proximity from each fish farm. Error bars are SE of means. CAL, Caletillas; CRIS, Los Cristianos; MEL, Melenara.

Table 2. Results of two-way uni- and multivariate ANOVAs testing for differences in the abundances of the most conspicuous species, the assemblage structure and the species richness of macrofauna with varying proximity ('Distance', fixed factor) from three fish farms ('Farm', random factor, orthogonal to 'Distance'). Significant differences are highlighted in bold. (CAL, Caletillas; CRIS, Los Cristianos; MEL, Melenara).

Source	df	MS	F	P	Pairwise comparisons for 'Distance × Farm'
<i>Ampelisca brevicornis</i>					
Distance	5	1.8924	0.86011	0.5392	CAL: ns
Farm	2	49.166	267.3	0.0002	CRIS: ns
Distance × Farm	10	22.002	11.962	0.0002	MEL: 40 m > 20, 60 m, Control 1 > 0 m, Control 2
Residual	36	0.18394			
<i>Apsuedes talpa</i>					
Distance	5	1.975	0.747	0.5998	CAL: 0 m, Control 1, Control 2, 0 m > 20, 40, 60 m
Farm	2	24.129	80.812	0.0002	CRIS: 60, 40, 20 m, Control 1, Control 2 > 0 m
Distance × Farm	10	2.642	8.849	0.0002	MEL: 60, 40, 20 m, Control 1, Control 2 > 0 m
Residual	36	0.298			
<i>Platynereis dumerilii</i>					
Distance	5	11.369	0.972	0.4616	CAL: ns
Farm	2	24.324	54.47	0.0002	CRIS: ns
Distance × Farm	10	11.698	26.195	0.0002	MEL: 0 m > 20, 40, 60 m, Control 1, Control 2
Residual	36	0.446			
<i>Dasybranchus caducus</i>					
Distance	5	9.077	1	0.4242	CAL: ns
Farm	2	13.241	93.111	0.0002	CRIS: 0 m > 20, 40, 60 m, Control 1, Control 2
Distance × Farm	10	9.077	63.833	0.0002	MEL: ns
Residual	36	0.142			
<i>Ditrupa arietina</i>					
Distance	5	3.772	0.905	0.5114	CAL: ns
Farm	2	22.788	20.97	0.0002	CRIS: Control 1, Control 2 > 0, 20, 40, 60 m
Distance × Farm	10	4.167	3.835	0.0002	MEL: ns
Residual	36	1.086			
<i>Urothoe marina</i>					
Distance	5	13.855	6.422	0.008	CAL: Control 1, Control 2 > 0, 20, 40, 60 m
Farm	2	5.215	13.145	0.0002	CRIS: ns
Distance × Farm	10	2.157	54.379	0.0002	MEL: Control 1, Control 2 > 0, 20, 40, 60 m
Residual	36	0.396			
<i>Scoloplos armiger</i>					
Distance	5	3.085	0.705	0.646	CAL: ns
Farm	2	11.623	37.83	0.0002	CRIS: ns
Distance × Farm	10	4.373	14.234	0.0002	MEL: Control 2 > 40, 60 m > Control 1, 0, 20 m
Residual	36	0.307			
Macrofaunal assemblage structure					
Distance	5	5269.3	1.1735	0.2132	CAL: 0 m, 20 m ≠ 40, 60 m ≠ Control 1, Control 2
Farm	2	16,423	21.017	0.0002	CRIS: 0 m ≠ 20, 40, 60 m ≠ Control 1, Control 2
Distance × Farm	10	4490.1	5.7459	0.0002	MEL: 0 m ≠ 20, 40, 60 m, Control 1, Control 2
Residual	36	781.44			
Species richness					
Distance	5	38.756	0.6213	0.689	CAL: 0, 20, 40, 60 m > Control 1, Control 2
Farm	2	36.222	2.072	0.1402	CRIS: 0, 20, 40, 60 m, Control 1 > Control 2
Distance × Farm	10	62.378	3.5682	0.0018	MEL: Control 1 > 0, 20, 40, 60 m, Control 2
Residual	36	17.481			

(Figure 3B) and *Scoloplos armiger* (Figure 3F) at Melenara, *Ditrupa arietina* (Figure 3D) at Los Cristianos and *Urothoe marina* (Figure 3G) at Caletillas and Los Cristianos (Table 2, pairwise comparisons).

Faunal assemblages with varying proximity to fish farms: assemblage-level patterns

Proximity to fish farms affected macrofaunal assemblage structure: faunal assemblages at 0 m were different from those found at controls at the three fish farms (Figure 4, PERMANOVA, pairwise comparisons, Table 2). However, pairwise differences in assemblage structure among distances

away varied among fish farms (Table 2). At Caletillas, fauna at 0 and 20 m away were not different in terms of assemblage structure, while fauna at controls differed relative to fauna at 40 and 60 m away (Figure 4A, Table 2). At Los Cristianos, the macrobenthic fauna at the controls also differed, in terms of assemblage structure, relative to the fauna at 40 and 60 m away (Figure 4B, Table 2). Fauna at 0 m differed, in terms of assemblage structure, from all other stations at Melenara (Figure 4C, Table 2). Species richness showed inconsistent patterns with proximity among fish farms (Figure 5, Table 2). Species richness was lower at controls than at 0, 20, 40 and 60 m at Caletillas (Figure 5, Table 2, pairwise comparisons), while at Los Cristianos no significant differences were detected (Figure 5, Table 2). At Melenara, we

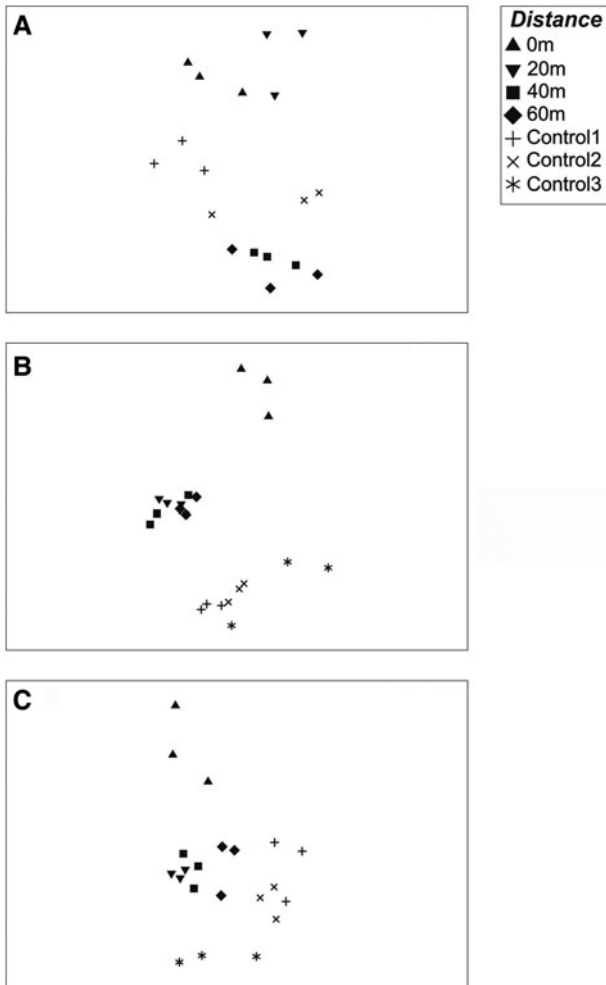


Fig. 4. Ordination plots (nMDS) showing similarities in macrofaunal assemblage structure at varying proximity from each fish farm: (A) Caletillas (stress = 0.11), (B) Los Cristianos (stress = 0.08) and (C) Melenara (stress = 0.14).

only detected a significant difference in species richness between controls and at 60 m distance from the cages (Figure 5, Table 2, pairwise comparisons).

DISCUSSION

Faunal assemblages with varying proximity to fish farms: species-level patterns

Our results showed that some species significantly decreased their abundances with increasing distance from some fish farms. For example, the polychaetes *Dasybranchus caducus* and *Platynereis dumerilii* were almost exclusively found in sediments beneath sea-cages, particularly at Los Cristianos and Melenara fish farms, respectively. The capitellid *D. caducus* has been previously collected in organic-enriched sediments on shallow areas (Bigot *et al.*, 2006). This species is a motile deposit-feeder and selective in its ingestion of sediment (Fauchald & Jumars, 1979), being attracted to organic loads released from fish cages (Junyi *et al.*, 2007). Indeed, this species belongs to a family (Capitellidae) widely found in sediments beneath aquaculture facilities under different

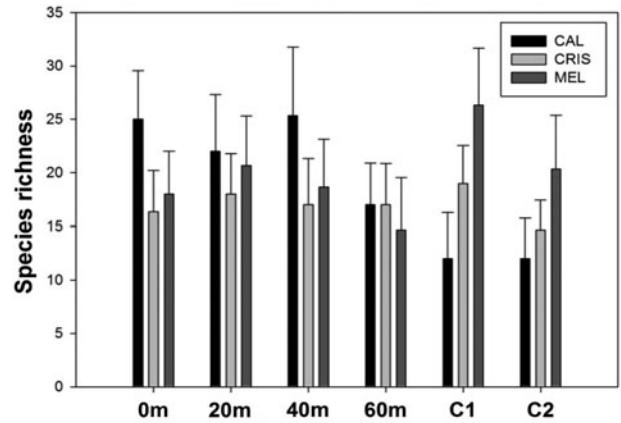


Fig. 5. Species richness at varying proximity from each fish cage. Error bars are SE of means. CAL, Caletillas; CRIS, Los Cristianos; MEL, Melenara.

culture scenarios, such as salmon farms in Scottish lochs (Nickell *et al.*, 2003), off-shore fish cages in the Mediterranean Sea (Karakassis *et al.*, 2000) and intertidal oyster cultures in New Zealand estuaries (Forrest & Creese, 2006). The nereidid *P. dumerilii* has been frequently found in organically enriched sediments as well (e.g. Musco *et al.*, 2009), including sublittoral bottoms affected by off-shore aquaculture activities (Cook *et al.*, 2006). In turn, *P. dumerilii* is considered as an opportunistic species able to fulfil its energy needs from different diets, and it is attracted by the organic load from sea-cage fish farms (Henderson & Ross, 1995). In our study, the former two species (*D. caducus* and *P. dumerilii*) were exclusively observed in fine-grained sediments (fine and very fine sands) beneath fish cages at Los Cristianos and Melenara farms. Both species have a preference for this type of sediment; *P. dumerilii* can burrow rapidly into the sediment to avoid predators (Chapman, 1958) and *D. caducus* lives in mucous-lined tubes or burrows that are built of fine sediments (Blake, 2000).

The polychaetes *Ditrupa arietina* and *Scoloplos armiger*, as well as the amphipod *Urothoe marina*, significantly increased their abundances with increasing distances from fish cages. The filter-feeder *Ditrupa arietina* has a preference for fine sands and muddy sediments (Gremare *et al.*, 1998); well-sorted fine sands are a suitable sediment type for the construction of the tube in young post-metamorphic juveniles (Gremare *et al.*, 1998). This fact can explain its presence on seabeds beneath cages at Los Cristianos farm, which was characterized by fine and very fine sands. The sub-surface deposit feeder *Scoloplos armiger* is more abundant in fine sediments (Rice *et al.*, 1986), which explains its presence beneath cages at Melenara farm (dominated also by fine and very fine sands). However, competition may have excluded this polychaete from sediments immediately beneath fish cages, since it is not well-adapted (i.e. low growth rate and low food conversion rate) to changing conditions compared with other polychaete species. In fact, *S. armiger* has been observed to be excluded by opportunistic polychaetes (e.g. the surface deposit feeder *Pygospio elegans*) in sediments beneath an intertidal clam culture facility in the Philippines (Spencer *et al.*, 1997). The detritivorous amphipod *Urothoe marina* is considered as a very sensitive species to organic enrichment (Borja *et al.*, 2000), including in the Canary archipelago (Riera *et al.*, 2012). This species is probably displaced by

opportunistic species; for example, due to competition for food with the nereidid *Platynereis dumerilii*, since the latter species lives on the top surface of the sediment and hence can take advantage of the excess of organic enrichment (Quintana *et al.*, 2010).

In contrast to our observations, a former study (Monterroso *et al.*, 2004) conducted in another fish cage from the Canary Archipelago showed a dominance of the tanaid *Apseudes talpa* in sediments beneath fish cages, as well as high abundances of the polychaetes *Galatowenia oculata*, *Myriochele danielsseni* and *Aricidea assimilis*. The most abundant species was the fire-worm, *Hermodice carunculata*, which formed aggregates of hundreds of individuals beneath fish cages (Monterroso *et al.*, 2004). This species, however, was exclusively represented by one single specimen in our study. Such an outcome might be explained by seasonal variations, i.e. the present study was conducted in spring–summer whilst the other was accomplished in winter (Monterroso *et al.*, 2004). Polychaetes such as *Hermodice carunculata* can show a remarkable spatial variability at scales ranging from hundreds of metres to tens of kilometres (Martin *et al.*, 1993; Frojan *et al.*, 2005).

Faunal assemblages with varying proximity to fish farms: assemblage-level patterns

Differences in macrofaunal assemblage structure of sediments located immediately beneath cages relative to the controls were found for the three fish farms. However, differences in macrofaunal assemblage structure at varying proximity to the cages in relation to controls varied among fish farms. Similarly, there were inconsistent patterns in species richness with varying proximity among fish farms. Our results have shown that the area directly affected by off-shore aquaculture, in terms of the macrofaunal assemblage structure, was $\sim < 20$ m in Los Cristianos and Melenara and < 40 m in Caletillas, similar to what Vita & Marin (2007) observed, and thus reduced compared with other studies, e.g. 80–180 m (Lee *et al.*, 2006; Edgar *et al.*, 2010). The hydrodynamic conditions around each fish farm affect the spatial extent of the organic enrichment from the fish cages, since low current intensities ($1.4\text{--}1.6\text{ cm s}^{-1}$) trigger the deposit of organic matter beneath fish farms (Kutti *et al.*, 2007). For example, Cromey *et al.* (2002) showed that current speeds $> 5\text{ cm s}^{-1}$ are strong enough to keep organic particles (i.e. fish faecal material and pellets) re-suspended. Aguado-Gimenez *et al.* (2007) found an affected area of less than 200 m around off-shore fish cages (36–38 m deep) in an area of mean current velocity of 26.9 cm s^{-1} . Thus, the current intensity largely determines the footprint of offshore cages.

In several studies, the spatial change in macrofaunal abundances and diversity caused by off-shore aquaculture followed the Pearson–Rosenberg model (Pearson & Rosenberg, 1978). Briefly, the largest abundances, biomasses and species richness of macrofauna peak at intermediate levels of organic enrichment, while there is an abrupt decrease in abundances and richness at higher levels of organic enrichment, i.e. directly beneath cages (Karakassis *et al.*, 2000; Edgar *et al.*, 2010). Our results, however, showed that macrofauna did not follow this model, as has been also previously reported for off-shore fish cages in the Mediterranean Sea (Aguado-Gimenez

et al., 2007; Vita & Marin, 2007; Sanz-Lazaro *et al.*, 2011) and other European areas (Carroll *et al.*, 2003; Mayor *et al.*, 2010). Despite it being plausible that the organic load was not large enough to produce consistent changes over macrofaunal assemblages, we lack data to unambiguously make this conclusion. This is actually the normal result given the emphasis on sustainable aquaculture practices (Sanz-Lazaro *et al.*, 2011). A wider sampling scheme through time would have provided more solid conclusions. In summary, inconsistent patterns of macrofaunal assemblages with varying proximity to aquaculture facilities do not allow solid predictions on the way offshore aquaculture alters macrofauna for the study region. Site-specific peculiarities seem then to be relevant and should be accounted for to adequately work out the effects of offshore aquaculture on recipient assemblages.

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